Hoegy

January 30, 2003 SUBMITTED TO BAMS Paper 1455

SHADOZ (Southern Hemisphere Additional Ozonesondes) - A Tropical Ozonesonde-Radiosonde Network for the Atmospheric Community

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ABSTRACT. A lack of sounding data has limited the accuracy of ozone satellite retrievals in the tropics and our understanding of chemical-dynamical interactions in a region strongly influenced by natural variability and anthropogenic activity. In 1998, NASA's Goddard Space Flight Center, NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) and a team of international sponsors established the SHADOZ (Southern Hemisphere ADditional OZonesondes) project to address the gap in tropical ozone soundings. SHADOZ augments launches at selected sites and provides a public archive of ozonesonde and radiosonde data from twelve tropical and subtropical stations at http://croc.gsfc.nasa.gov/shadoz. Instrumentation, data and a summary of the first scientific findings from SHADOZ are presented.

Background

The Ozonesonde Measurement

Although ozone-measuring satellites have been collecting data since 1970 [Heath et al., 1975], validation of profiles and total column measurements is still performed by a relatively low-technology instrument, the ozonesonde. An electrochemical concentration cell (ECC) ozonesonde, in which air pumped through a pair of cells containing potassium iodide solution initiates an electric current proportional to the amount of ozone in the atmosphere, is flown with a standard radiosonde. The ozone current is transmitted back to a ground receiver and the partial pressure of ozone is recorded with the pressure-temperature-humidity readings of the radiosonde. Designed to measure ozone concentrations from the surface to above the ozone concentration maximum (10-20 hPa), the combined ozonesonde-radiosonde package is flown with a 1200-1500 g balloon that usually bursts at 4-8 hPa. Figure 1 shows an ozonesonde during its preflight-testing and assembly with radiosonde prior to launch.

Figure 2 shows the raw data (relative humidity, temperature, ozone pressure, left panel) and ozone amount (right panel) in volume mixing ratio, the unit most commonly used by atmospheric chemists. Note that stratospheric ozone (the "good" ozone shielding the earth from ultraviolet radiation) is present at > 1 ppmv (part-per-million by volume) whereas tropospheric ozone (sometimes referred to as "bad" or "smog" ozone) is counted in parts-per-billion, ppbv. Background surface ozone ranges from 10-40 ppbv, depending on geographical location. On a highly polluted day in the United States - called "Code Red" in some areas - surface ozone may exceed 150 ppbv. The column integrated amount

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of ozone is measured in mm-atm or Dobson Units (DU), which is named after G. M. B. Dobson who began routine ozone measurements in the 1920's; for a review see Staehelin et al. [1998]. One Dobson Unit corresponds to 2.69 x 10 (16) molecules above 1 cm^2 or a thickness of 0.1 mm at standard temperature. The thickness of all ozone molecules is typically 0.25-0.45 cm-atm or 250-450 Dobson Units. The lower values typify a naturally thinner ozone column over the tropics. The highest values occur near the poles, except during ozone depletion when the value drops to less than 100 DU.

Presently there are about 50 stations sending data from ozonesondes to the World Ozone and Ultraviolet Data Centre, <http://msc-smc.ec.gc.ca/woudc>, in Toronto, an on-line archive operated by Environment Canada. In addition to providing ground-truth and climatologies for satellites, ozone profiles are used for evaluation of chemical models and the determination of ozone and temperature trends [WMO, 1998a; Randel et al., 1999]. Most northern hemisphere ozonesonde stations date from the 1960's and 1970's. The only tropical station in the southern hemisphere that has operated ozonesondes routinely for more than a decade is at Natal, Brazil [Logan and Kirchhoff, 1986; Kirchhoff et al., 1988].

Tropical Ozone and Meteorological Issues

In the late 1980's and 1990's satellite data focused attention on ozone in the tropics. At the equator, the TOMS (Total Ozone Mapping Spectrometer) total ozone record showed evidence of a zonal standing wave-one pattern, as well as cyclical variability in total ozone attributed to the Quasi-Biennial Oscillation (QBO), a shifting in the direction of mid-stratospheric wind direction [Shiotani, 1992]. Interannual variability in total ozone correlates with the El-Niño-Southern Oscillation (ENSO). Interactions among perturbed dynamics, precipitation and biomass fires in the tropics due to 1980's and 1990's ENSO events affected tropospheric ozone seen from satellite [Chandra et al., 1998; Fujiwara et al., 1999; Kita et al., 2000; Thompson et al., 2001].

In the south tropical Atlantic, a seasonal maximum in total and tropospheric ozone observed from satellite was attributed to large-scale savanna burning [Fishman et al., 1986; 1990]. Ozone soundings at Brazzaville (Congo, 4S, 15E), Ascension Island (8S, 15W) and Natal, Brazil (6S, 35W) confirmed that pollution ozone was indeed concentrated in layers transported from regions of African and South American burning [Cros et al., 1992; Olson et al., 1996]. During September-October, tropospheric column ozone may exceed 50 Dobson Units (DU) over Africa and the tropical Atlantic, compared to 10-25 DU in April or May [Thompson et al., 1996]. Ozone pollution from African fires frequently crosses the Indian and Pacific Oceans, where it has been detected in soundings over Réunion Island [Baldy et al., 1996], Java [Komala et al, 1996], the Galapagos, Tahiti, Samoa and Fiji [Oltmans et al., 2001].

In contrast to the tropical Atlantic, tropospheric ozone over the Pacific is frequently very low - column amounts < 10 DU are not unusual [Kley et al., 1996]. Net photochemical production destruction of ozone throughout the Pacific troposphere [Thompson et al, 1993] leads to very low surface ozone (< 5 ppbv). Convective mixing of low ozone concentrations at the surface helps maintain low concentrations aloft [Piotrowicz et al., 1991].

The aforementioned observations summarize our knowledge of tropical ozone up to 1998. Only 200-300 soundings from the tropics were available to the scientific community and there was no consistency in launch frequency, instrumentation, and geographical coverage. Stations started and stopped with campaigns, so trends and mechanisms could not be determined with any reliability. The following questions could not be answered:

- Does tropical ozone in the stratosphere and troposphere vary longitudinally and seasonally? If so, which processes are responsible?
- What causes the wave-one pattern in total ozone? Is the wave in the stratosphere, the troposphere or both?
- How do tropical dynamics contribute to ozone variability? What is the relationship between ozone and the QBO, El-Nino and Indian Ocean Dipole?
- Can the ozone climatology for satellite and model evaluation be improved? Is the current set of profiles used in typical satellite algorithms, longitudinally, latitudinally, seasonally invariant, accurate? Adequate? Are new ozone products from satellite accurate, e.g. estimates of tropospheric ozone column depth?

SHADOZ PROJECT AND DATA

In order to ensure that sufficient numbers of soundings are available throughout the tropics we initiated the SHADOZ (Southern Hemisphere Additional Ozonesondes) project in 1998, putting together a network of 9 stations according to the following criteria:

- operational - to avoid startup costs and to leverage off local support and infrastructure;
- contributing to a geographical distribution, spanning the entire longitude range;
- weekly launches, with the project sometimes supplying additional sondes (hence the name) in exchange for all the sonde data from the location.
- unrestricted website access by the community to the complete SHADOZ dataset.

The 9 stations stretched from the western Pacific and eastern Indian Oceans across to South America, Africa and La Réunion, an island east of Madagascar. Since late 1998, three more stations have joined the network, including one in the northern tropics (Surinam) that displays distinct influences from the southern hemisphere [Peters et al., 2002]. All stations are listed in Table 1.

More than 1700 sonde profiles for the twelve stations (Figure 3) are available at the SHADOZ website <http://croc.gsfc.nasa.gov/shadoz>, including 80 profiles from four tropical campaigns of opportunity. Experimental details, latitude and longitude of each station and personnel contact information are given in Thompson al. [2003a]. In addition to the data and graphical display of the sounding, the air parcel history of each sounding is depicted at the website. These are based on 5-day back trajectories run with the NASA/Goddard kinematic trajectory model [Schoeberl and Newman, 1995] at four standard pressure levels using data from the 2.5x2.5-degree NCEP reanalysis. For the sounding shown in Figure 2, Figure 4 shows the corresponding trajectories.

HIGHLIGHTS OF SHADOZ OBSERVATIONS

Evaluation of Sonde Performance.

To date, what do SHADOZ data tell us? First, by having so many data points taken under mostly tropical conditions, we have learned something about the ozonesonde measurement [Thompson et al., 2003a]. It turns out that although all SHADOZ stations use the ECC sonde, small variations in instrument type (manufacturer) and preparation procedures may affect the ozone measurement. Statistics from the first large set of tropical ozone soundings show the following:

- The precision of the total ozone column by a single instrument is 5%. Realize that each sonde launched is essentially a new instrument and this figure refers to the reproducibility of an individual sounding.
- Comparison with ground-based instruments (four Dobson spectrophotometers and

one Brewer spectrometer) showed excellent agreement between integrated total ozone from the sondes, 2-5% with the best agreement at the two African stations, Irene (near Pretoria, South Africa) and Nairobi, Kenya.

- Comparison with total ozone from the TOMS satellite shows a greater degree of variability (2-11%) among stations, with the satellite measurement always higher.

The precision of the ozonesonde instrument deduced from SHADOZ may be better than previous evaluations [WMO, 1998b] because SHADOZ samples are taken in a fairly uniform meteorological regime and with similar technique.

Ozone Variability and Meteorology

Second, the SHADOZ data, with unprecedented coverage both spatial and temporal, have provided striking examples of the links among tropical meteorology, ozone and pollution [Thompson et al., 2003b]. We illustrate this through the following examples.

Wave-one.

One of the most dramatic results from SHADOZ has been the first look at the structure of the standing wave-one in tropical ozone and an answer to the "where is the wave" question. The wave-one is seen to be predominantly if not completely in the troposphere. Figure 5 shows the wave-one pattern in total and tropospheric ozone for March-April-May (MAM) and September-October-November (SON) and Figure 6 shows a cross-section of the wave for SON with the partial pressure contours based on 0.25-km averaged segments.

Free tropospheric ozone has a lifetime up to a month or more, so the patterns in Figure 6 are quite stable. How does the wave come about? It apparently results from photochemical activity, dynamical patterns and general circulation. Ozone is most concentrated in the free troposphere over eastern South America, Atlantic, Africa and the Indian Ocean (40W-90E). In this region, photochemical sources (biogenic, from biomass burning, lightning formation of ozone precursors) are most concentrated [Pickering et al., 1996; Moxim and Levy, 2000]. Furthermore, subsidence is prevalent over the south tropical Atlantic where mid-tropospheric ozone accumulates [Krishnamurti et al., 1996]. The high-ozone feature over the Atlantic-African region is supported by a persistent recirculation of ozone pollution in an anticyclonic high pressure system [Garstang et al., 1996; Tyson et al., 1997]. Pollution also heads east from Africa toward Réunion. Over the eastern Indian and Pacific Oceans (Watukosek and Fiji-Samoa-Tahiti), free tropospheric ozone is a minimum because convection brings clean, lower tropospheric ozone to the middle and upper troposphere. Similar patterns to those seen in SHADOZ sondes prevailed over the tropical Atlantic Ocean during the SAFARI/TRACE-A field campaigns [Fishman et al., 1996] in September-October 1992. At that time, sondes showed that the free tropospheric south Atlantic ozone maximum is composed roughly equally of background ozone and pollution. Two-thirds of the pollution was from Africa, the remainder from South America [Thompson et al., 1996].

Qusai-Biennial Oscillation

Besides the wave-one pattern and the imprint of general circulation in the SHADOZ data, another large-scale dynamical feature has been detected. Prior to SHADOZ, sounding data were neither frequent enough nor close enough to the equator (where the QBO effect is most pronounced) to fully document the ozone response to the QBO. In the stratosphere, near the ozone mixing ratio maximum (25-27 km), the QBO variation is evident in many SHADOZ profiles [Logan et al., 2002]. The QBO, a downward propagating oscillation between easterly and westerly winds, has a period of about 28 months [Reed, 1964]. In the first half of 1998 the winds above 30 hPa (~24 km) are easterly; throughout the year there is a shift to westerly winds that causes the ozone to increase at that pressure, over and above the normal seasonal increase. Examples of profile changes for 1998 appear in Figure 7. The reader is referred to Logan et al. [2003] for complete discussion of the QBO, SHADOZ sondes and concurrent satellite data.

Variability and Pollution, Convection, Stratosphere-troposphere Exchange.

One of the surprising results of SHADOZ is the large seasonal and meteorological variability seen in tropospheric ozone. At individual sites, curtain graphs (altitude vs time) show that week-to-week variability in ozone is a record of short-term meteorological change. In many cases advection of pollution alternates with convection. Pollution leads to high ozone mixing ratios in the mid-troposphere (green and yellow at Nairobi in Figure 8A) and convection brings up low-ozone air and cleans it out. The convective signature is corroborated by the variability in relative humidity (Figure 8B), where the higher relative humidity, blue above 8-10 km, shows redistribution of air from the surface.

The variability in SHADOZ tropospheric ozone is seen in sites both near and far away from the equator. Comparison of the ozone profiles at Ascension Island (8S, 15W) with those at Lauder, New Zealand (45S; Figure 9) shows that below 10 km the seasonal variation is larger at Ascension. Similarly, a comparison between Réunion (21S) with Hohenpeissenberg, Germany (48N) indicates that the tropical site has at least as great a variability as seen at the northern hemisphere mid-latitude station.

There are two practical consequences of the variability of ozone at SHADOZ sites. One is that simple averaged profiles, typically used for analysis of trends, may not be statistically robust. This is evident in Figure 10, depicting seasonally averaged mean ozone at Nairobi (a representative SHADOZ site) for four years, along with the individual profiles that comprise the mean. Rather than using averages to describe the ozone profile at a site, it may be more appropriate to categorize profiles according to synoptic regime [Diab et al., 2002] and to analyze changes within each distribution.

Second, we see the degree of ozone fluctuations that must be captured by satellites and models designed to follow ozone pollution. For example, simulation of convective episodes observed in SHADOZ tests convective parameterizations in models. Given what we have learned about ozone variability from SHADOZ, one can see why daily (or better, geostationary) views are the ultimate goal of satellite development, not filtered monthly averages used in many studies. It may be that new approaches are needed. One possibility is an assimilation model with photochemistry, well-resolved sources and transport, in which SHADOZ data are ingested to produce accurate ozone profiles and satellite ozone column amounts. The latter would allow us to follow global ozone pollution from region to region, country to country and globally.

SHADOZ TEMPERATURE RECORDS

Although the SHADOZ PTU (pressure, temperature, humidity) soundings have not been used as widely as ozone observations, the archive offers a unique set of radiosondes. An example of temperatures below 20 km appears in Figure 8C. Temperature measurements from both resistive-type (VIZ/Sippican) and capacitive type (Vaisala) thermistor are used in SHADOZ; each has a relationship with ozone. The two types of sensors do not provide identical values [Schmidlin, 1988; Nash and Schmidlin, 1987]; differences in the stratosphere can exceed 1-1.5°. Capacitive thermistor data are corrected in the sonde software at each station. Resistive thermistor measurements are not corrected at the station but may be when used by analysis centers, e.g. NCEP.

Temperature data from Natal, Brazil for 2001 were averaged for each month to produce values shown in the contours of Figure 11. Up to about 150 hPa the contours appear laminar although small ripples in the unsmoothed data would be due to local weather events. The two most striking features of the 2001 Natal temperature data are: (A) tropopause variability: -80C between 90 and 200 hPa from January through April; an increase to -(75-70)C between April and November. (B) Temperatures increase with time at pressures lower than 60 hPa, e.g. from -60C in January to -50C in December.

SHADOZ PARTICIPATION IN CAMPAIGNS

Aerosols99 and SAFARI-2000 Campaigns

To give a larger range of tropical coverage, SHADOZ station data have been augmented with ozone launches from field campaigns in which the interaction of ozone chemistry and meteorological processes has been studied. The campaign data are also available at the SHADOZ website.

An Atlantic cruise on the *R/V Ronald H. Brown* in January and February 1999 showed that tropical tropospheric ozone profiles north of the ITCZ may be very different from south of the ITCZ. The shipboard measurements showed convective influence north of the ITCZ, and an ozone column 4-5 DU lower than south of the ITCZ where ozone accumulated in descending air. In Figure 12, the convection is signified by better mixing and a more uniform ozone and humidity profiles (solid lines); the higher ozone with drier air (dashed lines) represents conditions south of the ITCZ. Satellite data showed that the hemispheric ozone contrast was characteristic of the entire tropical Atlantic. Because biomass burning added pollution north of the ITCZ, the expectation had been that the greater ozone column would be to the north. Instead greater column ozone is south of the ITCZ, a phenomenon referred to as the "ozone paradox" [Thompson et al., 2000; Martin et al., 2002; Jenkins et al., 2002].

A campaign at Lusaka, Zambia, during SAFARI-2000 [Swap et al., 2002] confirmed the absolute stability of pollution layers during the southern African dry season, a phenomenon first discovered during SAFARI/TRACE-A in 1992 [Garstang et al., 1996]. Recirculation of this pollution ozone over south central Africa produced very high tropospheric ozone throughout the free troposphere, in contrast to relatively clean profiles often found at fixed SHADOZ sites. Biomass burning over Angola, Namibia, Zimbabwe, Mozambique, as well as South Africa and Zambia itself contributed to a layer of pollution ozone > 100 ppbv over Lusaka [Thompson et al., 2002]. Figure 13 shows a curtain graph of ozone mixing ratio, averaged in 1-km layers, for each of nine launches in SAFARI-2000. A localized disturbance, following the fifth sounding, cleaned out the boundary layer and reduced ozone aloft, but the absolutely stable layer at 2-3 km remained intact. In addition to the pollution aloft, boundary layer ozone during the first four launches exceeded 90 ppbv, the highest level yet measured over southern Africa. Up to one-half of this pollution appeared to be from local vehicles and urban burning practices [Thompson et al., 2002].

JOSIE

The WMO is developing a standard procedure for ozonesonde operations to be used at GAW (Global Atmospheric Watch) stations. Because of slight variations in technique across SHADOZ data, our stations are used to examine details of technique. In September 2000, SHADOZ investigators participated in JOSIE-2000 (Juelich Ozonesonde Intercomparison Experiment) under WMO sponsorship [WMO, 1998b]. All the methods used in SHADOZ were tested against a calibrated spectroscopic instrument in chamber tests conducted in Germany in September 2000 at the Forschungszentrum in Juelich,

<http://www.fz-juelich.de/ icg/icg2/forschung/Josie>. Preliminary analysis of results shows that instrument properties (manufacturer and concentration of the chemical solution) affect the ozone measurement and may account for small variations seen among SHADOZ stations when sonde total ozone is compared to a ground-based or satellite total ozone column [Thompson et al., 2003a]. A field comparison of sondes will be made in June 2003 under WMO sponsorship. A large balloon will be flown with a uv spectrophotometric ozone instrument and several sonde instrument types.

WMO's GAW seeks to increase the number of ozonesonde stations in developing countries. Several SHADOZ stations provide a model for GAW's "twinning" cosponsorship concept. Station operations, infrastructure and gases are provided by the country in which the station is located. A partner country initiates sonde launches with a local agency, either a meteorological department or a space institute. Training, expendables and data processing are provided by the outside sponsor. In this manner NASA and the Brazilian Space Agency (INPE) started the first tropical soundings in 1978 when the first TOMS (Total Ozone Mapping Spectrometer) satellite instrument was launched. Twinning between the Swiss Meteorological Agency and the Kenyan Meteorological Department led to the start of sonde launches at Nairobi in 1996. Other examples in SHADOZ are the Japanese and Indonesian Space Agency operation on Java and the meteorological services of the Netherlands and Surinam at Paramaribo.

SUMMARY

Nearly 2000 ozone and PTU profiles archived between 1998 and 2002 are now at the SHADOZ website: <http://croc.gsfc.nasa.gov/shadoz>. SHADOZ data have been used to improve the profile climatology for models and satellite algorithms, elucidate the structure of the zonal wave-one in tropospheric ozone, and delineate characteristics of the ozone response to the QBO. As NASA looks ahead to a 2004 launch of the AURA platform, SHADOZ is well poised for essential validation of the four ozone sensors on board.

Acknowledgments. SHADOZ is supported by NASA's Atmospheric Chemistry Modeling and Analysis Program (ACMAP) and the TOMS project. It would not exist without the generous and enthusiastic participation of the following: NASA's Wallops Flight Facility, NOAA, NASDA (National Space Development Agency of Japan), LAPAN (Lembaga Penerbangan dan Antariksa Nasional, the National Institute of Aeronautics and Space of Indonesia), INPE (Instituto Nacional de Pesquisas Espaciais, the National Space Agency of Brazil), the South African Weather Service, the Swiss Meteorological Agency, the Kenyan Meteorological Department, the Royal Dutch Meteorological Institute (KNMI), the University of the South Pacific (Suva, Fiji), CNRS and the University of Réunion Island (France). We are grateful to the WMO Global Atmospheric Watch project for the opportunity to participate in the JOSIE intercomparison activity.

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Captions.

Fig. 1 - (A) Photo of the electrochemical concentration cell (ECC) ozonesonde instrument. Potassium iodide sensing solutions are placed in the plastic cells. The inlet (blue tube at right) pulls air toward pump (below white junction); a second tube sends air into the cells. Behind the upright flat metal piece is the electronics board that transmits a current from the ozone sensor along with the radiosonde signal. The ozone current is proportional to the ozone partial pressure (Figure 2, left side). (B) An assembled ozonesonde, inside its styrofoam box, with radiosonde attached.

Fig. 2 Typical profile from the SHADOZ website, showing data in partial pressure (ozone, on left) and temperature from radiosonde (also left), with ozone volume mixing ratio (right) determined from the ratio of the ozone and total atmospheric pressures. Example sounding was taken on 17 October 2001 from Ascension Island. High ozone peaks below 10 km originate from African regions with biomass burning.

Fig 3 - SHADOZ sites. Station latitude-longitude information is in Table 1.

Fig 4 - Five-day back trajectories, initialized at pressure levels shown with color code, run with the GSFC kinematic trajectory model [Schoeberl and Newman, 1995], initialized with NCEP winds, as indicated. + marks each 24-hr transit segment.

Fig. 5 Total and tropospheric ozone for March-April-May (MAM) and September-October-November (SON), depicted as column-integrated amounts. Lower tropospheric ozone over Nairobi is partly due to 1.3 km elevation at the site; this causes 3-6 DU less ozone than would be recorded at sea-level station with a similar profile.

Fig 6 - The structure of the zonal wave-one in tropospheric ozone from averaged SON data, 1998-2000. Between eastern South America and the western Indian Ocean, ozone and sources of photoreactive ozone precursors are more concentrated during biomass burning or lightning episodes. There is also a tendency for ozone to subside in that region, compared to convective tendencies over the central Pacific. Thus, more tropospheric ozone appears from 50W to 50E (Figure 5), giving a wave-like appearance to the integrated ozone column [Thompson et al., 2003b].

Fig 7 - Profiles over Nairobi, Kenya illustrate stratospheric ozone increases under the influence of the QBO in 1998 (October relative to February). In 1999 there was not a noticeable difference in February-October phases; profiles in 2001 were similar to those for 1998.

Fig. 8 - Week-to-week tropospheric variability at Nairobi, indicated in altitude-vs-timegraphs of the ozone mixing ratio (A) relative humidity (B), temperature (C) for 1998-2001. Means of 0.25 km are used. Nairobi uses a capacitive-type temperature sensor for which corrections are incorporated into the reduction software. Note that the correction is keyed to pressure and solar angle and thus is not specific to local environmental influences.

Fig. 9 - Variability, on an annually averaged basis, of tropospheric ozone at two mid-latitude locations (Hohenpeissenberg, Germany; Lauder, New Zealand) and two SHADOZ stations (Réunion and Ascension Islands). Soundings over the US, where tropical air masses in summertime are associated with very high pollution [Newchurch et

al., 2003] also show large variability.

Fig 10 - Nairobi seasonal mean profile (MAM=March-April-May) and SON (September-October-November) to 20 km, based on 4 years data, with individual profiles contributing to mean.

Fig 11 - Temperature contours for monthly averaged data for 2001 at Natal, Brazil.

Fig. 12 - Mean of profiles, ozone and relative humidity, taken north (solid) and south (dashed), respectively, of the ITCZ on the Aerosols99 cruise of the *R/V Ronald H. Brown* during a January-February 1999 Atlantic transect from Norfolk, Virginia to Cape Town, South Africa [Thompson et al., 2000].

Fig. 13 . Succession of 9 soundings, 1-km mean mixing ratio, taken from 6-11 September 2000, over Lusaka, Zambia (15.5S, 28E). Launches were made during SAFARI-2000 campaign [Thompson al., 2002]; the data reside in the SHADOZ archive.

Table 1. SHADOZ Stations. Further technical details given in Table A-1 in Thompson et al., [2003a].

Station	Latitude	Longitude	Co-Investigator/Sponsor	Operating Agency/Station Manager
Pago, Pago, American Samoa	-14.23	170.56	NOAA/CMDL, S. J. Oltmans	NOAA/CMDL
Papeete, Tahiti	-18.00	149.00	NOAA/CMDL, S. J. Oltmans	MéteoFrance
San Cristóbal, Galapagos	-0.92	89.60	NOAA/CMDL, S. J. Oltmans, H. Vömel	INAMHI (National Ins. Of Hydrology and Meteorology of Ecuador)
Paramaribo, Surinam	5.81	-55.21	KNMI, H. M. Kelder	Met. Service Surinam, C. R. Becker
Natal, Brazil	-5.42	-35.38	NASA/Wallops, F. J. Schmidlin	INPE, V. W. J. H. Kirchhoff, F. da Silva
Ascension Island	-7.98	-14.42	NASA/Wallops, F. J. Schmidlin	US Air Force
Irene, South Africa	-25.25	28.22	So. Africa Weather Service (SAWS), G. J. R. Coetzee	SAWS, N. A. Phahlane, D. Esterhuyse
Malindi, Kenya	-2.99	40.19	Univ. Rome, G. Laneve	Project San Marco
Nairobi, Kenya	-1.27	36.80	Méteosuisse, B. Hoegger, B. Calpini, G. Levrat	Kenya Met. Dept., W. Kimani
La Réunion Is.	-21.06	55.48	CNRS/Univ. Réunion, F. Posny	Univ. Réunion, F. Posny, J-M. Metzger
Watukosek, Java, Indonesia	-7.60	112.70	NASDA, T. Ogawa, S. Kawakami	LAPAN, S. Suripto
Suva, Fiji	-18.13	178.40	NOAA/CMDL, S. J. Oltmans	Univ. Pacific, K. Koshy

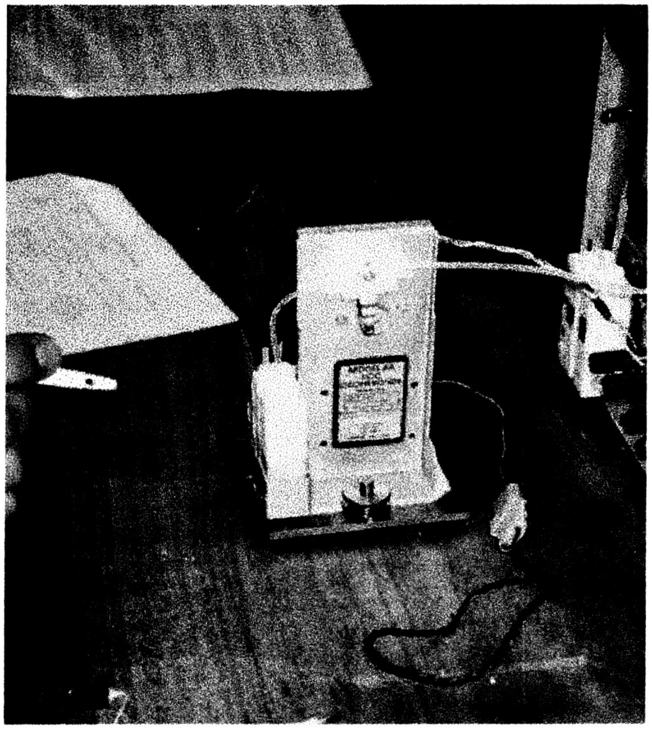


Fig 1a

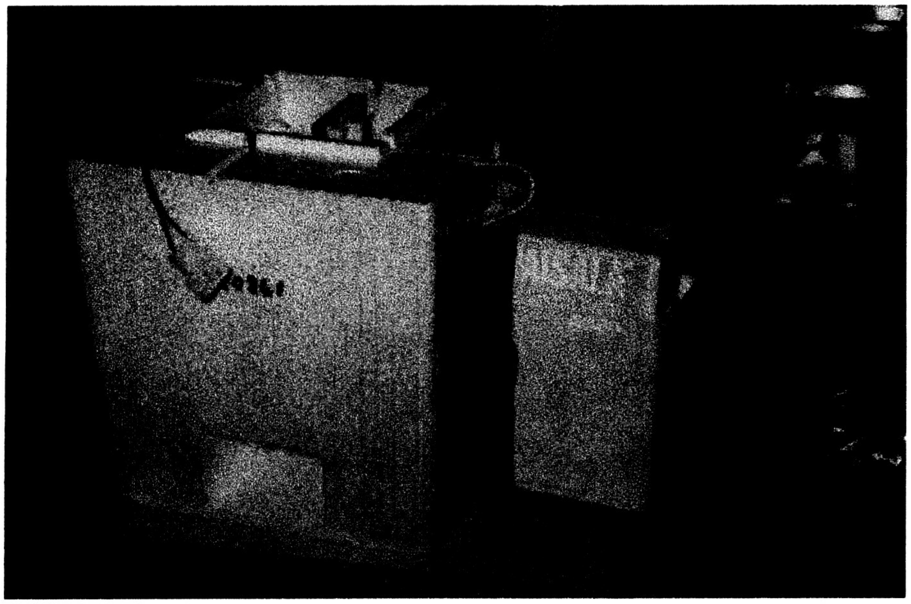


Fig 1b

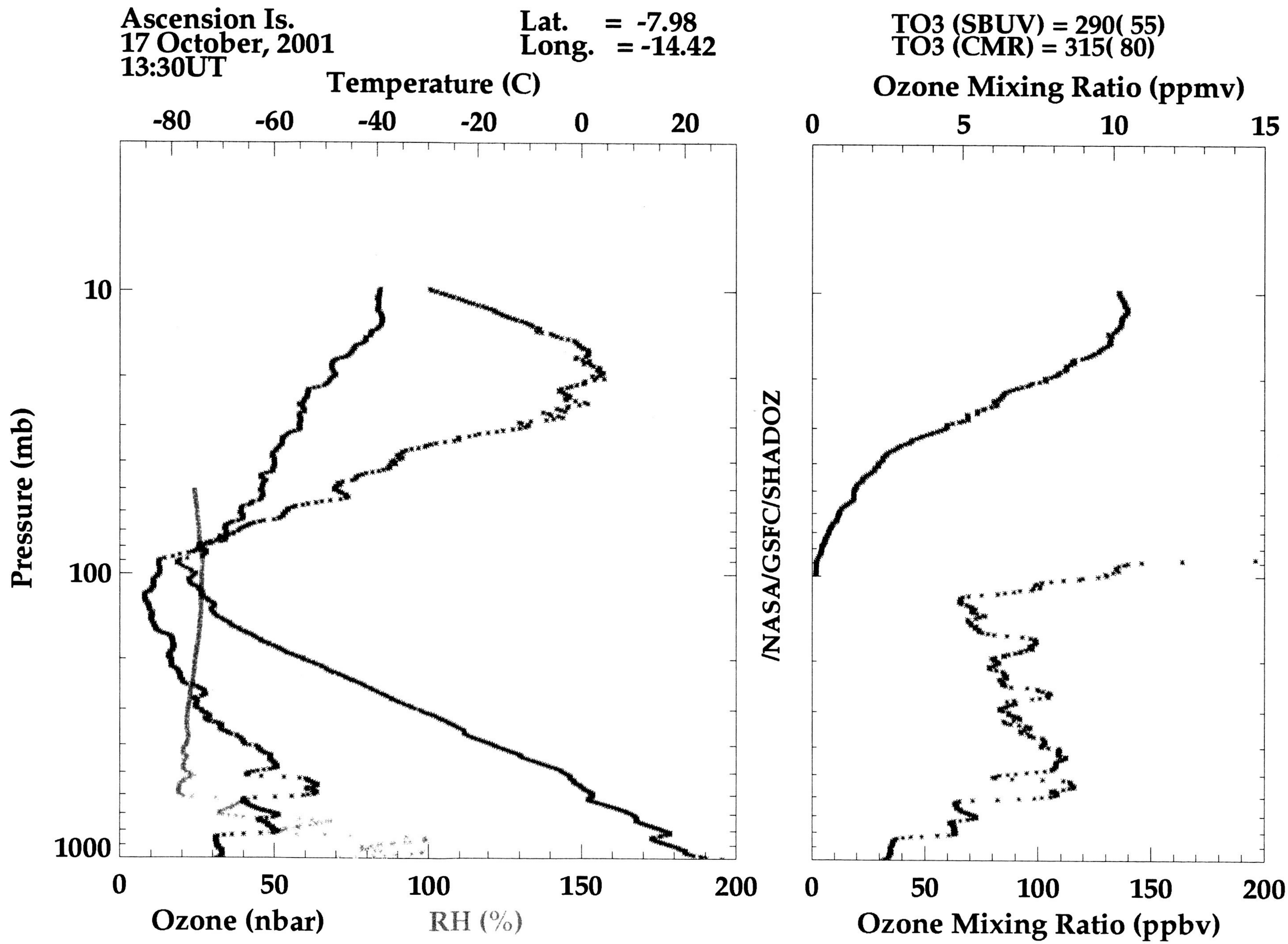

Ascension Is.
17 October, 2001
13:30UT
Lat. = -7.98
Long. = -14.42
TO3 (SBUV) = 290(55)
TO3 (CMR) = 315(80)
Temperature (C)
-80
-60
-40
-20
0
20
Ozone Mixing Ratio (ppmv)
0
5
10
15
Pressure (mb)
10
100
1000
/NASA/GSFC/SHADOZ
0
50
100
150
200
Ozone (nbar)
RH (%)
0
50
100
150
200
Ozone Mixing Ratio (ppbv)

Figure 2

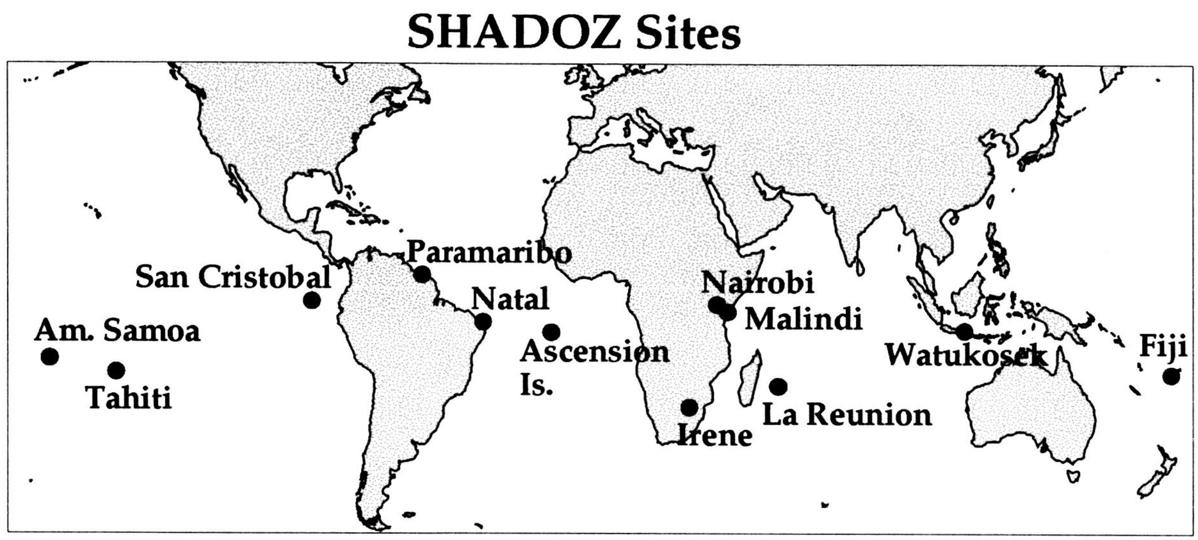

SHADOZ Sites
San Cristobal
Paramaribo
Natal
Am. Samoa
Tahiti
Ascension
Is.
Nairobi
Malindi
Irene
La Reunion
Watukosek
Fiji

Figure 3

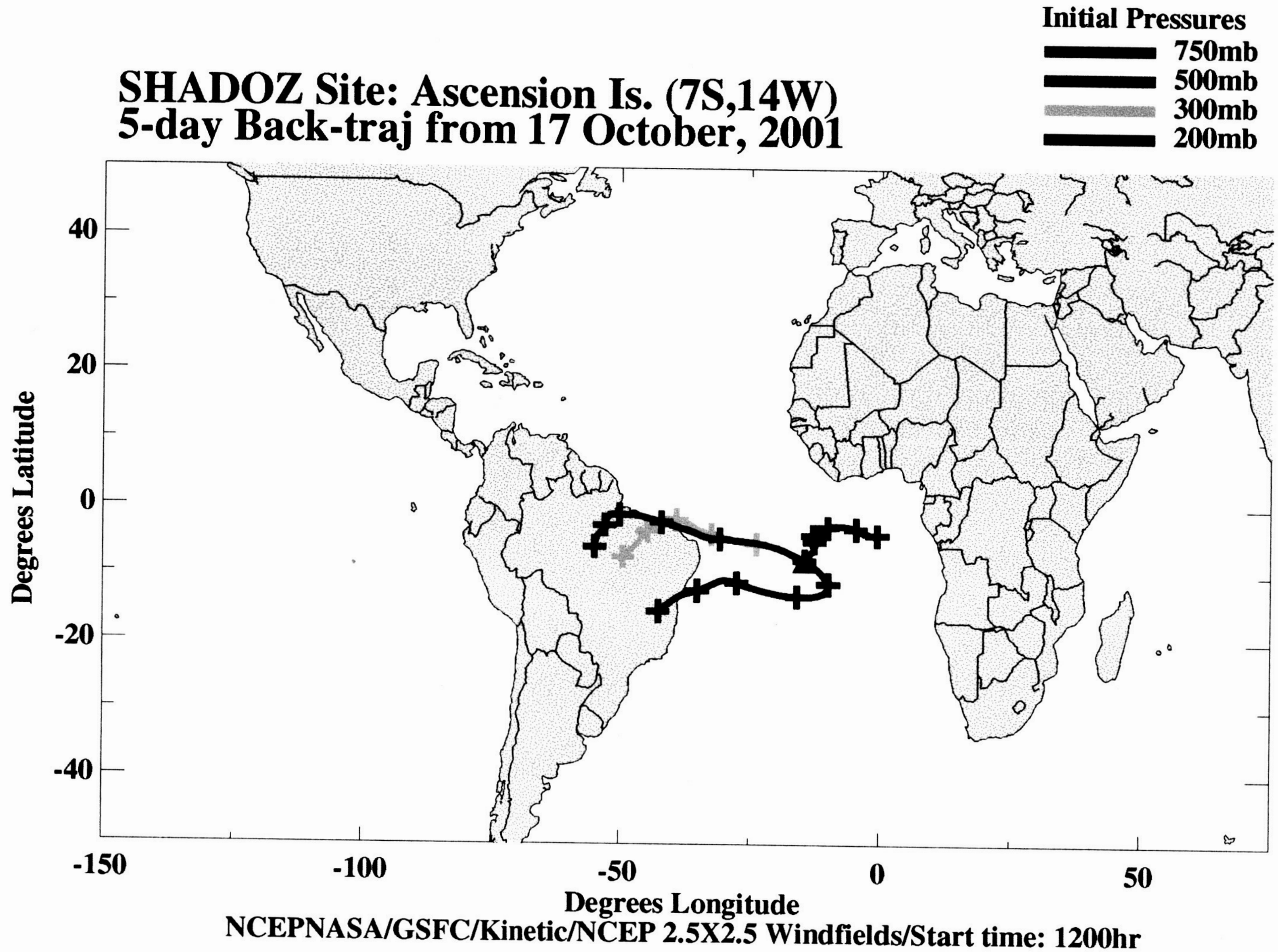

SHADOZ Site: Ascension Is. (7S,14W)
5-day Back-traj from 17 October, 2001
Initial Pressures
750mb
500mb
300mb
200mb
Degrees Latitude
40
20
0
-20
-40
-150
-100
-50
0
50
Degrees Longitude
NCEPNASA/GSFC/Kinetic/NCEP 2.5X2.5 Windfields/Start time: 1200hr

Figure 4

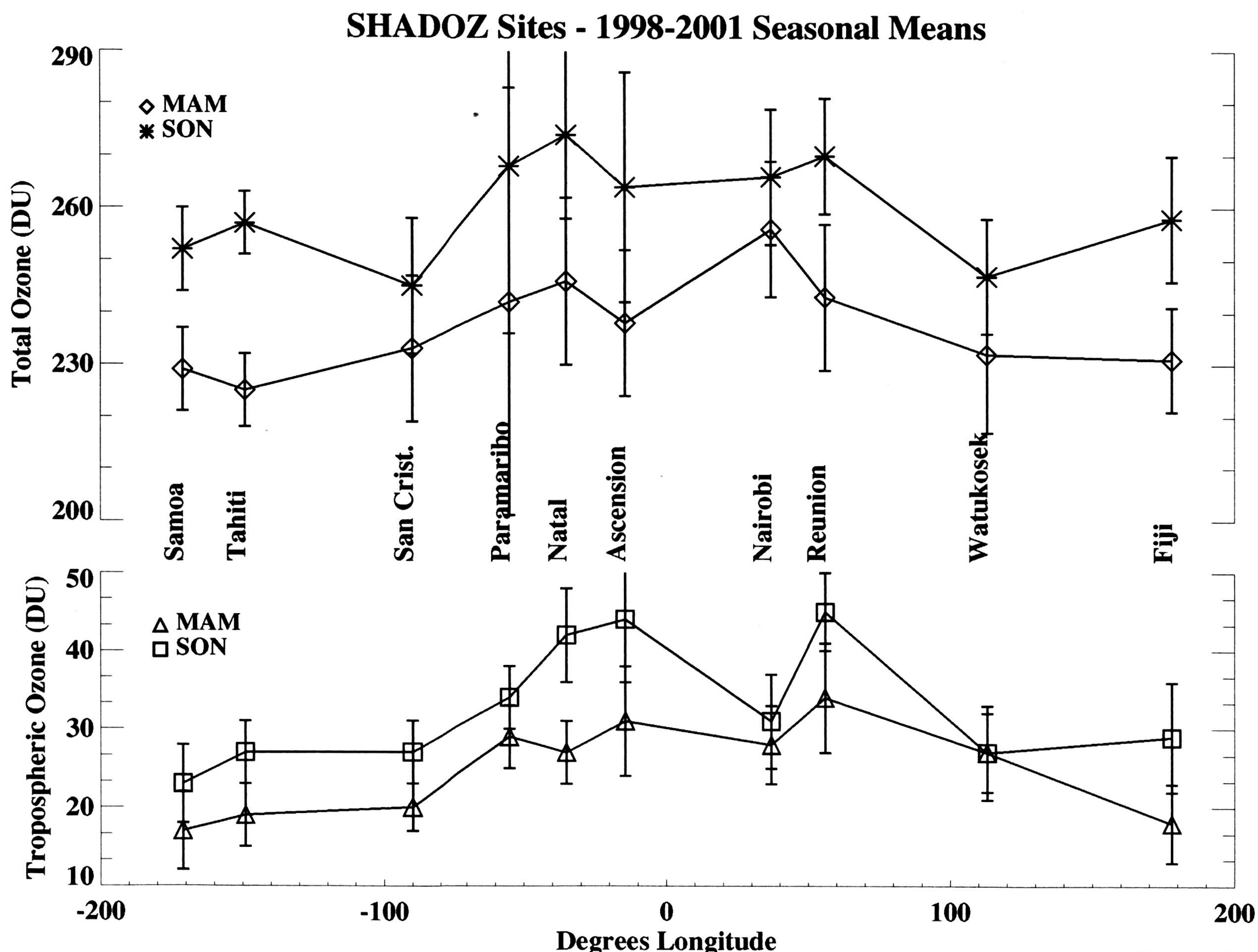

SHADOZ Sites - 1998-2001 Seasonal Means
Total Ozone (DU)
290
260
230
200
MAM
SON
Samoa
Tahiti
San Crist.
Paramaribo
Natal
Ascension
Nairobi
Reunion
Watukosek
Fiji
Tropospheric Ozone (DU)
50
40
30
20
10
MAM
SON
-200
-100
0
100
200
Degrees Longitude

Figure 5

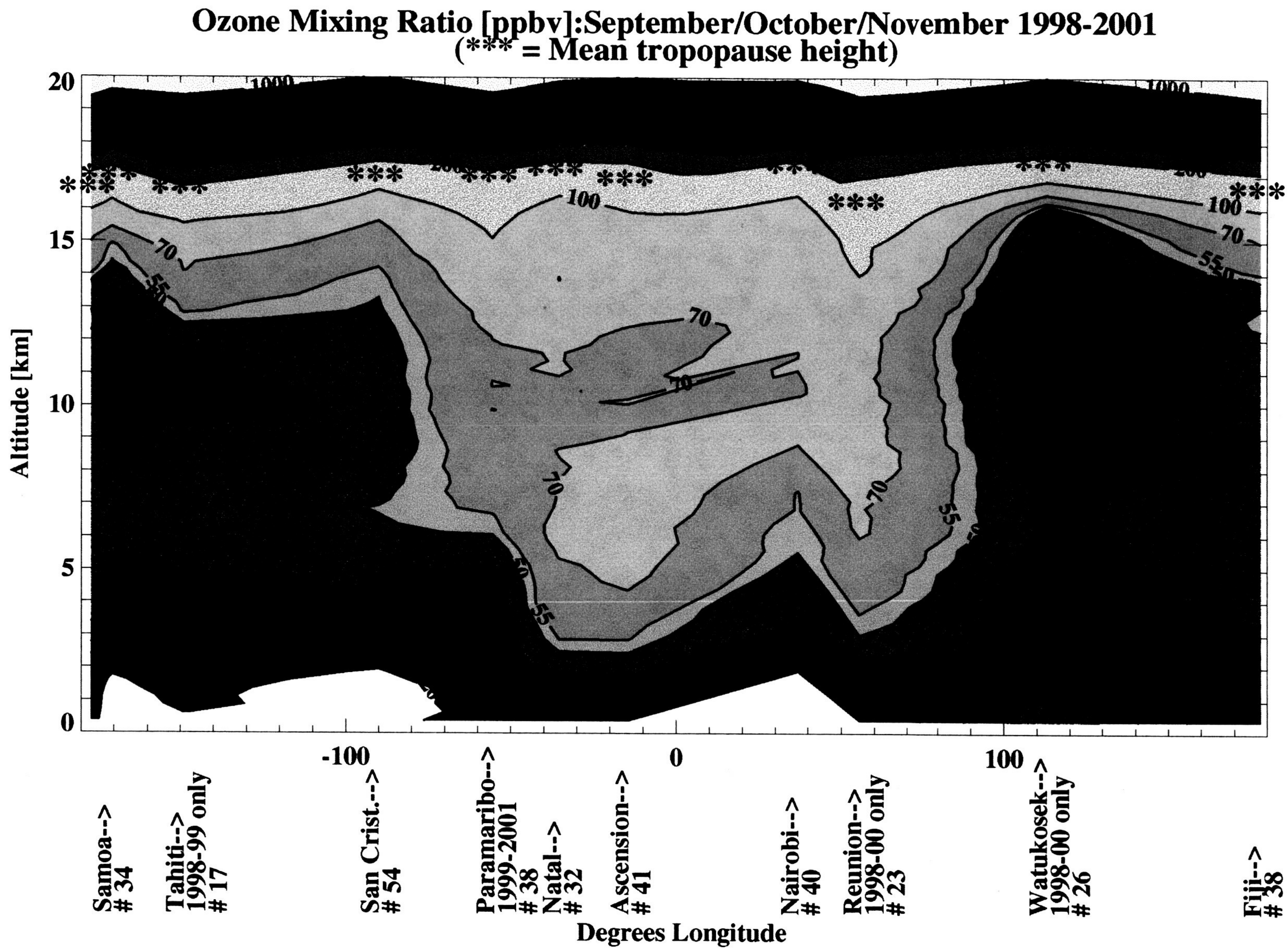

Ozone Mixing Ratio [ppbv]:September/October/November 1998-2001
(*** = Mean tropopause height)
Altitude [km]
20
15
10
5
0
-100
0
100
1000
100
70
55
50
Samoa--> # 34
Tahiti--> 1998-99 only # 17
San Crist.--> # 54
Paramaribo--> 1999-2001 # 38
Natal--> # 32
Ascension--> # 41
Nairobi--> # 40
Reunion--> 1998-00 only # 23
Watukosek--> 1998-00 only # 26
Fiji--> # 38
Degrees Longitude

Figure 6

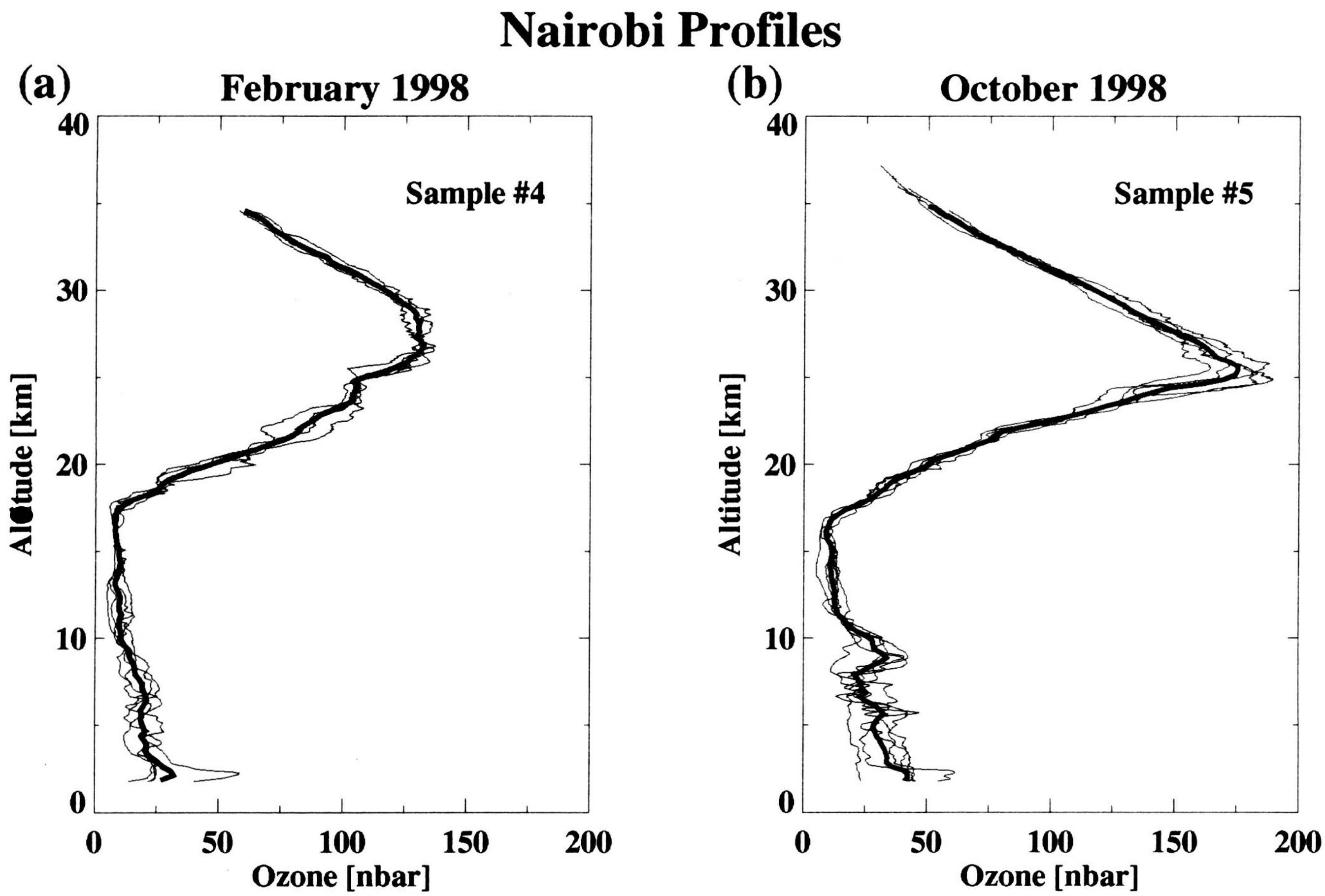

Nairobi Profiles
(a)
February 1998
Sample #4
Altitude [km]
Ozone [nbar]
0
50
100
150
200
0
10
20
30
40
(b)
October 1998
Sample #5
Altitude [km]
Ozone [nbar]

Figure 7

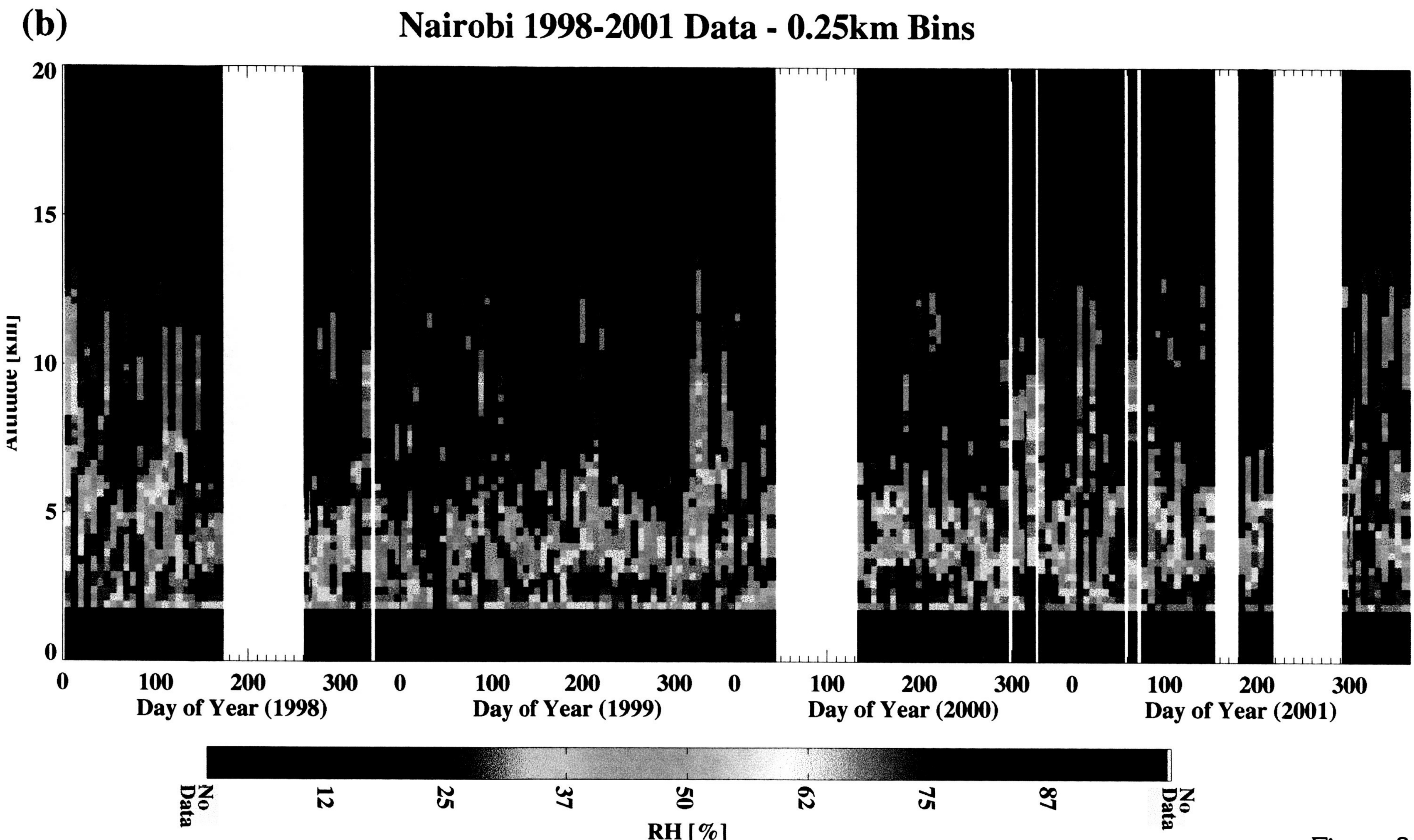

(b)
Nairobi 1998-2001 Data - 0.25km Bins
Altitude [km]
0
5
10
15
20
0
100
200
300
Day of Year (1998)
Day of Year (1999)
Day of Year (2000)
Day of Year (2001)
No Data
12
25
37
50
62
75
87
No Data
RH [%]

Figure 8

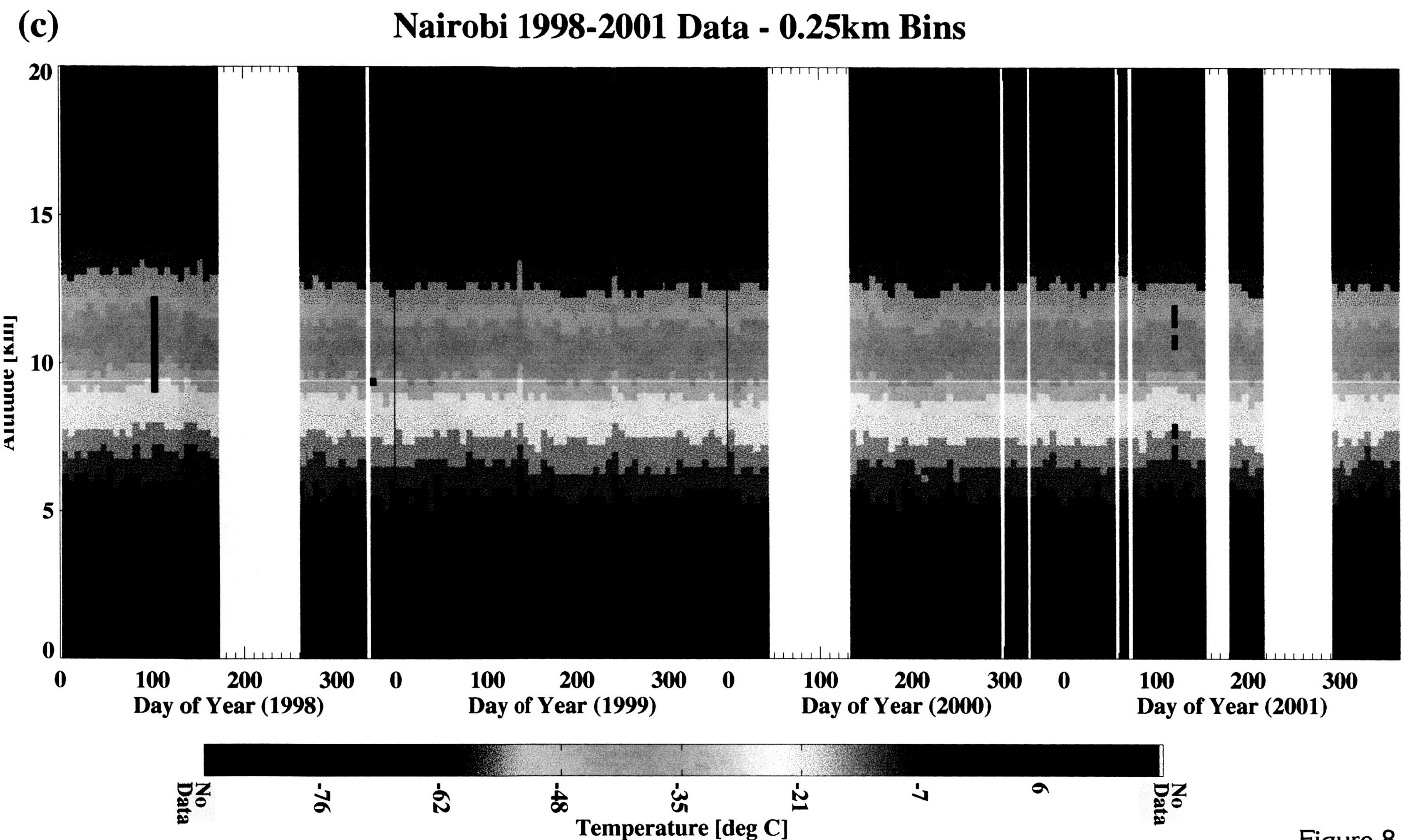
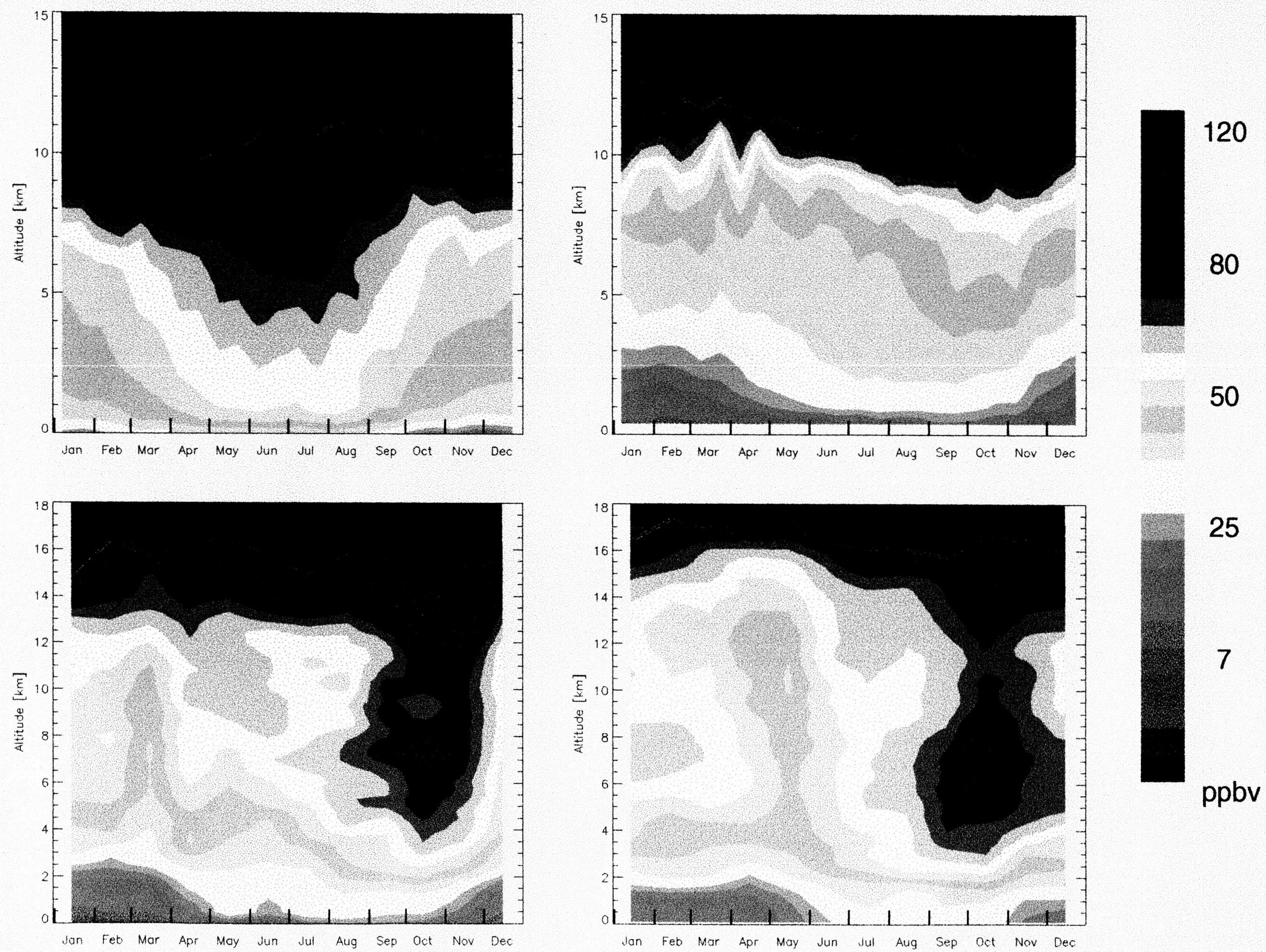

(c)
Nairobi 1998-2001 Data - 0.25km Bins
Altitude [km]
20
15
10
5
0
0
100
200
300
Day of Year (1998)
Day of Year (1999)
Day of Year (2000)
Day of Year (2001)
No Data
-76
-62
-48
-35
-21
-7
6
No Data
Temperature [deg C]

Figure 8

Figure 9: Comparison of mid-latitude and tropical tropospheric ozone seasonal cross-sections



Nairobi 1998-2001 Seasonal Profiles

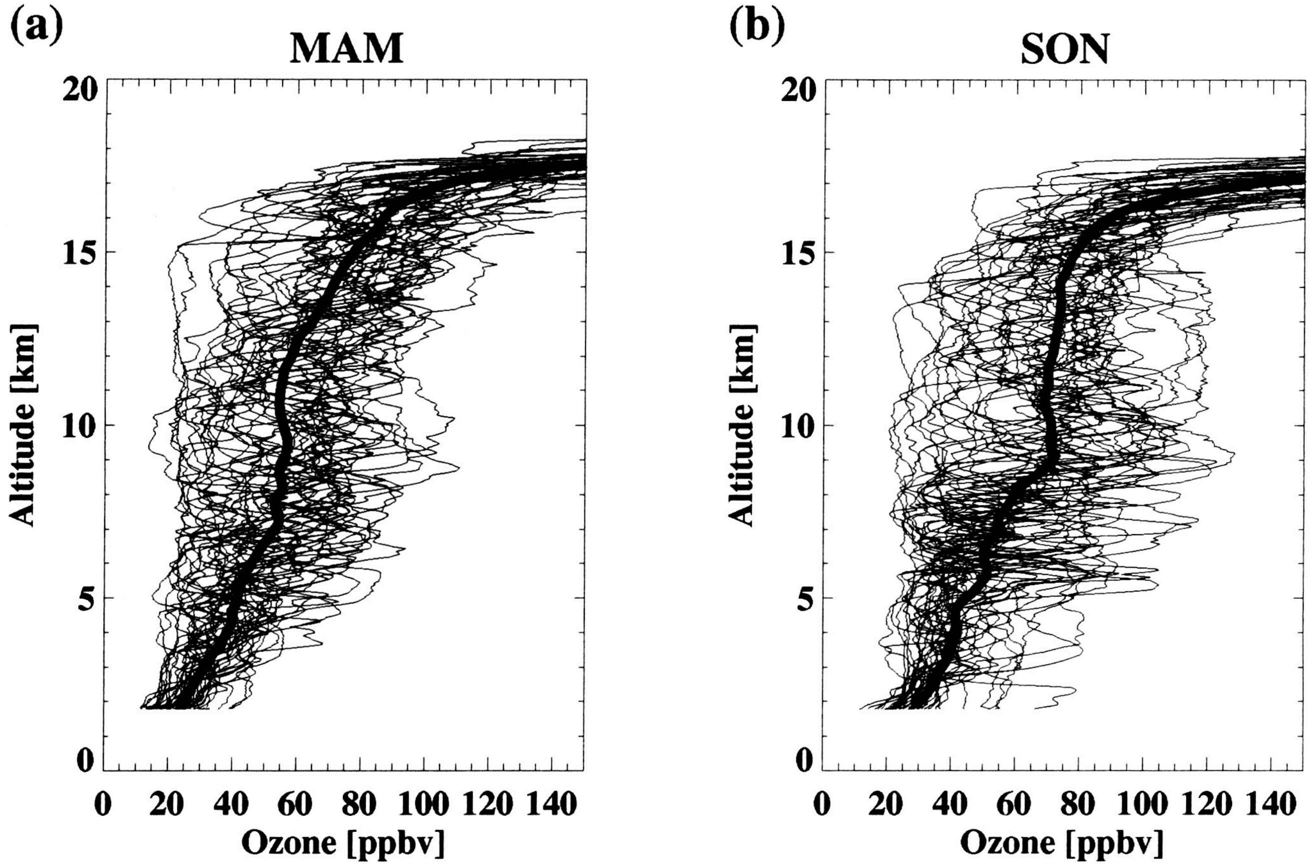


Figure 10

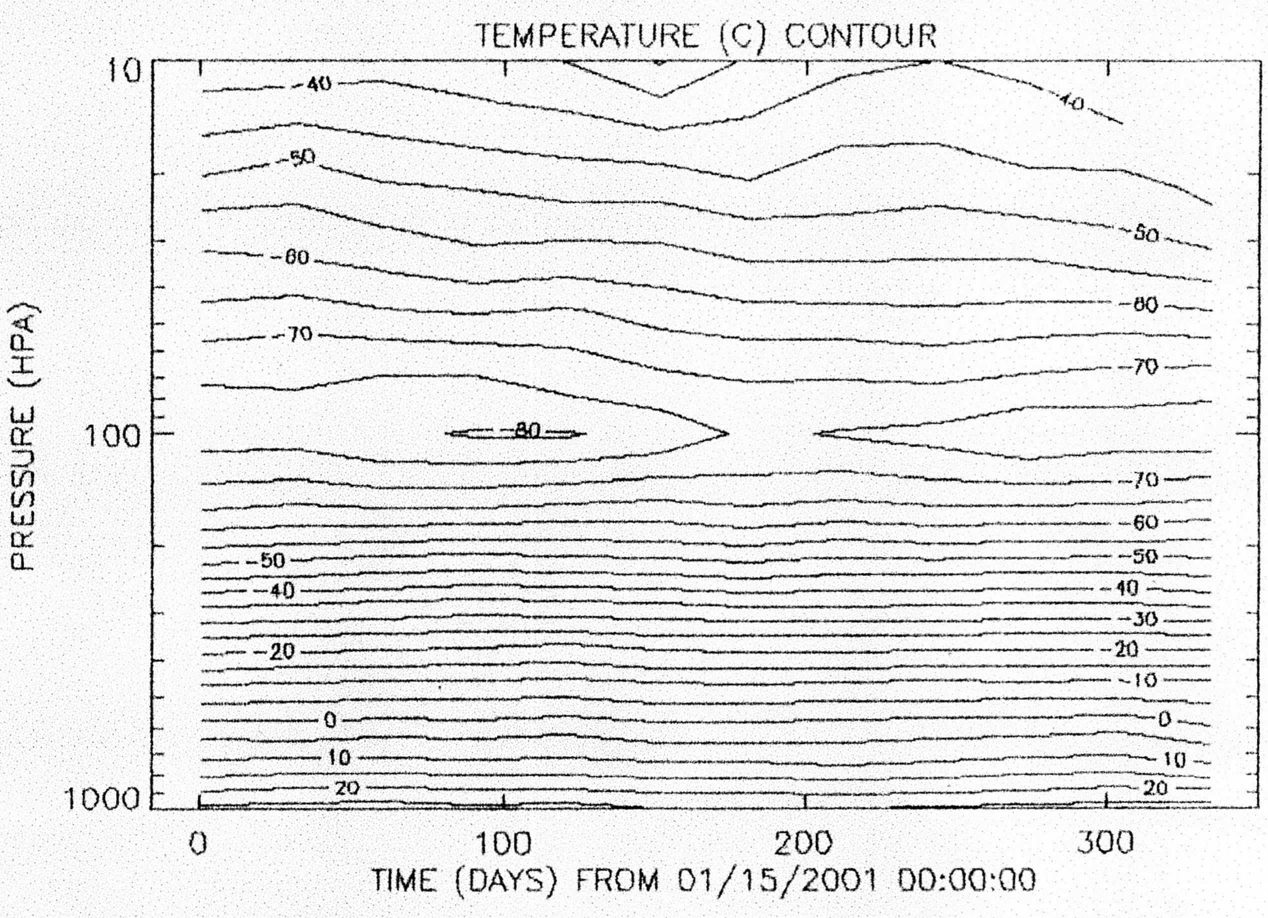

TEMPERATURE (C) CONTOUR
PRESSURE (HPA)
TIME (DAYS) FROM 01/15/2001 00:00:00
10
100
1000
0
100
200
300
-40
-40
-50
-50
-60
-60
-70
-70
-80
-70
-60
-50
-50
-40
-40
-30
-20
-20
-10
0
0
10
10
20
20

Figure 11

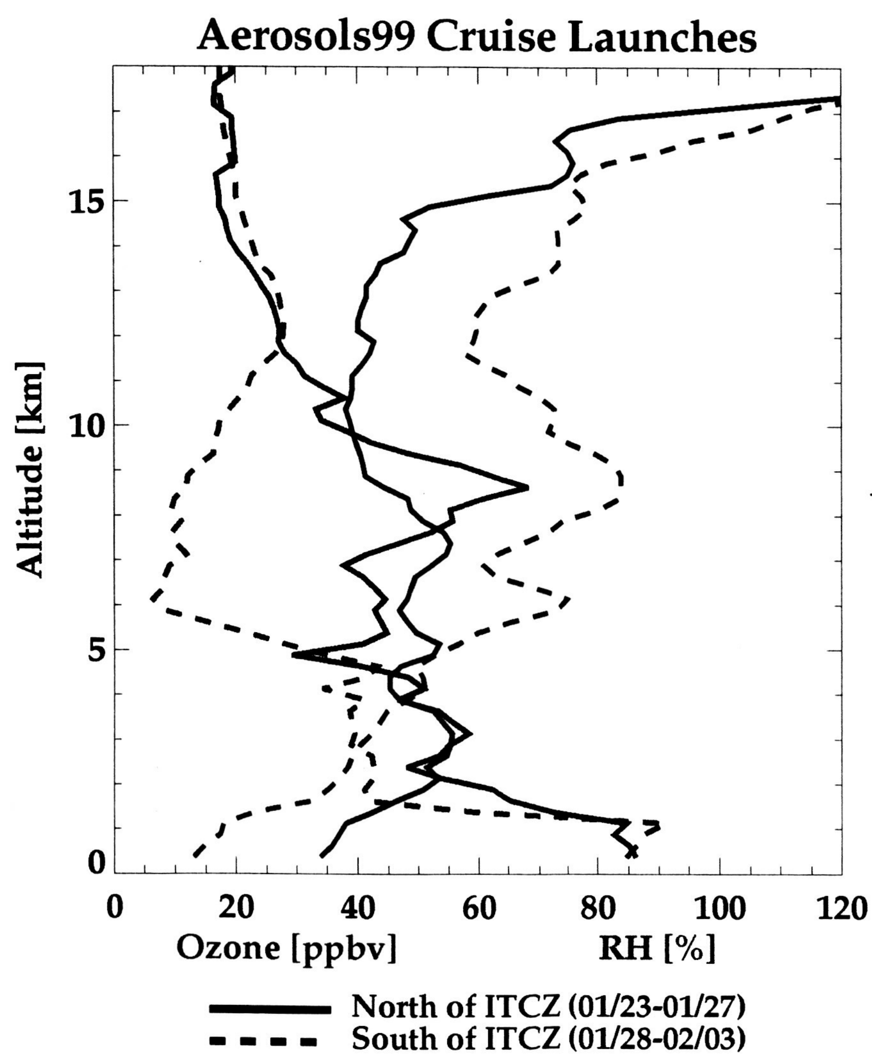

Aerosols99 Cruise Launches
Altitude [km]
0
5
10
15
0
20
40
60
80
100
120
Ozone [ppbv]
RH [%]
North of ITCZ (01/23-01/27)
South of ITCZ (01/28-02/03)

Figure 12

Lusaka, Zambia (15.5S, 28.3E) SAFARI-2K
Ozone Mixing Ratio (ppbv)

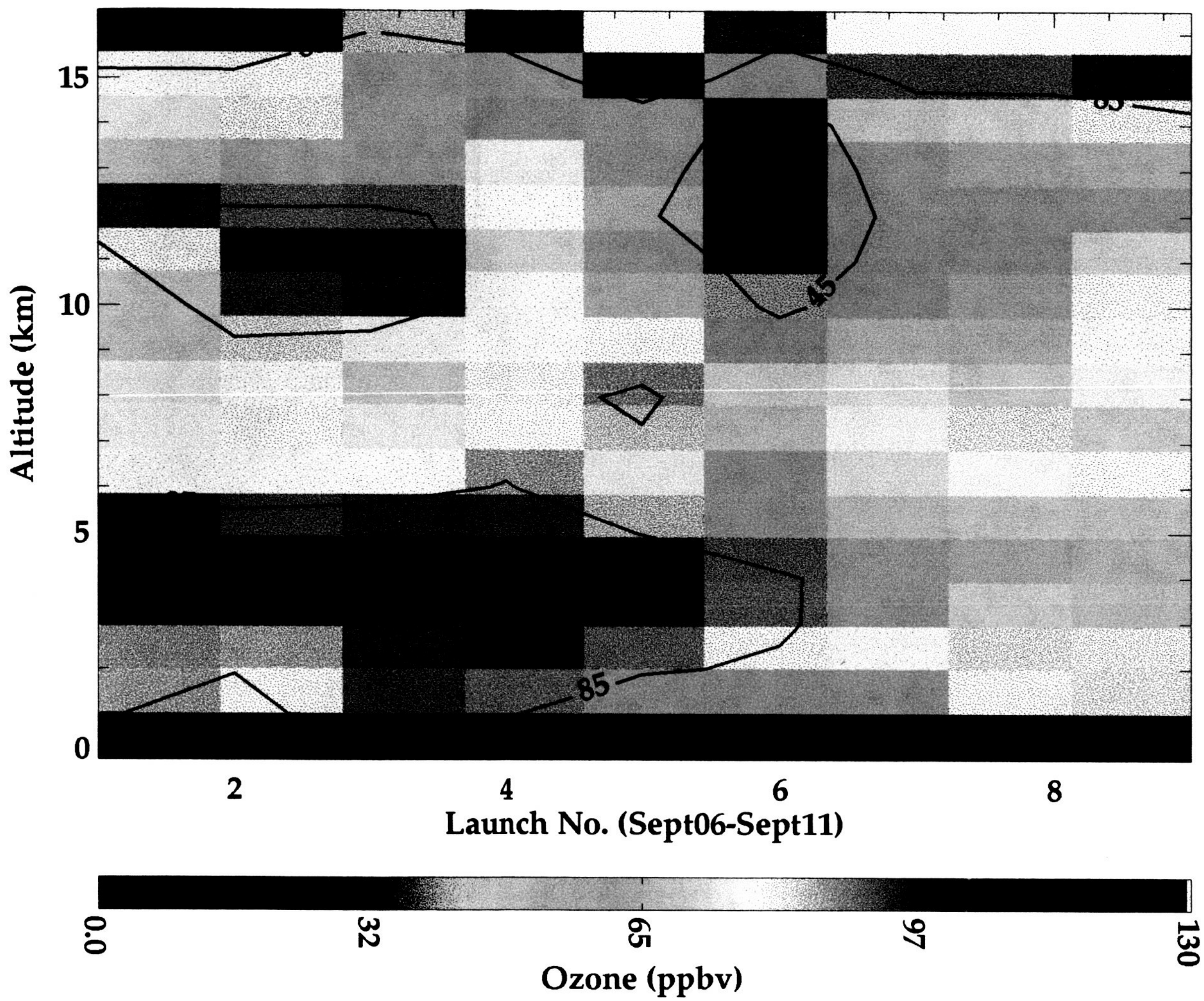


Figure 13

Popular Summary
for Paper submitted to BAMS-Bulletin of the Am Meteorological Society, Jan 03

SHADOZ (Southern Hemisphere Additional Ozonesondes) - A Tropical Ozonesonde-Radiosonde Network for the Atmospheric Community

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Samuel J Oltmans (NOAA/CMDL, Boulder, CO 80303)
Francis J Schmidlin at NASA/GSFC/Wallops Flight Facility, Wallops Is., VA 23337

This is an overview paper about the SHADOZ (Southern Hemisphere Additional Ozonesondes) network designed to interest the larger meteorological community in the data and the research. Following a description of what ozonesondes are, highlights of the first 3-4 years of data are described. Signatures of convection, the Quais-Biennial Oscillation and pollution from biomass burning all appear in SHADOZ ozone profiles. Also given are details of the zonal wave-one structure in tropospheric ozone and variability over the southern Atlantic, Pacific and Indian Ocean basins. The conclusion, new to the SHADOZ body of data (now > 1700 profiles) is that signals of climate effects, convection and offsets between biomass burning seasonality and tropospheric ozone maxima suggest that large scale dynamics as well as episodic meteorological systems are more important than pollution in determining the tropical distribution of tropospheric ozone. The SHADOZ data at <http://croc.gsfc.nasa.gov/ shadoz> continue to set records in website visits, second only to TOMS in Code 916.